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A Study on the Determinants of Decommissioing Cost for Nuclear Power Plant (NPP)

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Nuclear power plants (NPPs) produce radioactive waste and decommissioning this waste entails additional cost; determining these costs for various types and specifications of radioactive waste can be challenging. The purpose of this study is to identify major determinants of the decommissioning cost and their impact on NPPs. To this end, data from defunct NPPs were gathered and 2SLS (Two Stage Least Squares) regression models were developed to investigate the major contributors depending on the reactor types, viz. PWR (Pressurized Water Reactors) and BWR (Boiling Water Reactors). Additionally, cost estimations and the Monte Carlo simulation were performed as part of performance validation. Our study established that the decommissioning costs are primarily influenced by the level of radioactivity in the decommissioned waste, which can be realized from operational factors like operation period, overall efficiency, and plant capacity, as well as from duration of decommissioning and labour cost. While our study provides an improved statistical approach to recognize these factors, we acknowledge that our models have limitations in forecasting accurately which we envisage to bolster in future studies by identifying more substantive factors.

Keywords: Nuclear power plants, Decommissioning cost, Radioactive waste, 2SLS regression

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1. Introduction

Nuclear power plants (NPP), as any industrial facility, have a finite lifetime and thus shall be permanently suspended and dismantled if operation lifetime is not extended. The term 'decommissioning' refers to not only the administrative but also technical actions taken to allow the removal of the regulatory controls from a facility. The decommissioning of nuclear power plants shall be carried out after a permanent shutdown in accordance with relevant laws. Reasons for the permanent shutdown may be poor economic performance, political judgment, severe accidents, and in most cases, economic loss due to aged facility.

Decommissioning involves activities such as removal of fuel, dismantling of plant and equipment, decontamination of structures and components, demolition of buildings, remediation of contaminated ground and recycling or disposal of the resulting waste. Adequate planning and management are needed to ensure throughout implementation until the eventual de-licensing (license termination). Enhancing the regulatory controls that apply to a nuclear site, either entirely or partially, is one of the central decommissioning agenda, which is attained through the progressive and systematic reduction of radiological hazards [1]. Regardless of the end state of the decommissioned site, the underlying key requisite is to ensure the site to ensure public health and safety as well as protection of the environment, and the continued health and safety protection of workers [2].

According to the IAEA PRIS (2020), 442 nuclear power reactors are in operation as of September 2020. There are 192 nuclear power reactors that have been in operation for more than 30 years, 99 of them are over 40 years, and 8 of them are over 50 years [3]. As a result, reliable decommissioning cost estimation gets more importance not only for liability recognition but also for actual cost budgeting from the fiscal point of view.

The decommissioning schedule and a cost estimation can be elaborated through management tools such as WBS (Work Breakdown Structure) and ISDC (International Structure for Decommissioning Costing purposes) [4]. However, it is not easy to make predictions without detailed due-diligence data. There are various factors affecting decommissioning costs such as characteristics of nuclear power plants, operation efficiency, operating period, and regulatory requirements. And that, even a reactor with the same capacity may cause different decommissioning cost depends on the operating period, the decommissioning method, the residual values, and regulatory requirements. These tools cannot provide generalized decommissioning cost estimate for bundle of NPPs. In accordance with International Accounting Standards, every country should estimate decommissioning cost based on the characteristics of nuclear power plants in order to provide a basis for covering decommissioning cost with liabilities. It is necessary to scrutinize major factors that affect to the decommissioning cost as well as the degree of the monetary impacts.

Consequently, the goal of this paper is to empirically investigate major determinants and degree of their impact on the decommissioning cost. This paper may have academic contributions in threefold: presents comprehensive NPP decommissioning cost data though wide range of research, provides an enhanced regression models, and suggests a Monte Carlo simulation to increase practicality. Meanwhile, the limitations of this study are added in the conclusion.

In the second chapter, we review literatures on decommissioning cost estimation, cost drivers, and policy. Especially, we provide a historical set of permanent NPP shutdown data based on document research. In the third chapter, we introduce research models and basic statistics. In the fourth chapter, we present test result on the effective determinants of decommissioning cost achieved from regression analysis. In the fifth chapter, we show cost estimation result with confidence intervals and compare them against the authority's official estimation. Monte-Carlo simulation is also performed to check the fitness of suggested model. Finally, we wrap up paper with discussion and conclusion.

2. Literature review

There are not many previous literatures based on statistical analysis with historical cost data in regard to NPP decommissioning. One of the latest and meaningful literatures is Joo et al. (2020) [5]. They developed a multi-regression model to estimate the decommissioning cost of Kori-1, using the historical decommissioning data, which is comprised of 13 boiling water reactors (BWR) and 16 pressurized water reactors (PWR). They found out two major factors that determine the decommissioning cost: a contamination factor which is designed to reflect the operational characteristics, and a decommissioning work period of plants. They measured the contamination factor based on operation period, thermal capacity, and operation factor. They estimated the decommissioning cost range of Kori-1 between 663.4 mil and 928.3 mil USD based on the suggested cost formula.

Geoffrey et al. (2016) [1] provides data on decommissioning cost drivers in Europe and the United States. They suggest three main cost drivers and percent range of costs: dismantling activities (12–50%), project management (14–55%), and waste management (4–26%).

The cost for dismantling activity varies greatly depends on the national decommissioning strategy. The strategy of removing (as a whole or segmentation) large components radioactive waste, and the degree of site restoration and cleanup have been shown to have a significant impact to the dismantling activities. Especially, there is a significant difference in restoring cost of site depends on the degree of ground contamination.

The project management cost is not dependent on capacity but differs whether the project is managed by a licensee or an external contractor. Engineering and security, fixed-cost items take larger portion in smaller plants. In addition, project management cost differs depends on the number of reactors due to an efficiency and integration of project management. For example, a French case showed the lowest ratio of 14% in project management cost as there were four nuclear reactors in the same site.

The cost of radioactive waste management varies significantly in its range due to cost classification such as transporting and disposing of radioactive waste. In addition, it is determined by the usage of the constructed facility, expansion, and a need for new construction.

Monteiro et al. (2019) [4] introduced a management tool and mathematical model for estimating decommissioning budget. Their model aims to estimate the decommissioning cost for budgeting or bidding purpose. After a case study and sensitivity test, they suggested the critical factors are project length, difficulty factors, man-hour cost, waste treatment, remediation, planning length, and on-site exemption wastes.

Lararia et al. (2005) [6] analyzed the factors that determines decommissioning strategy of NPP. The decommissioning cost heavily depends on the national policy and strategy, which factors, of course, impact to the decommissioning cost. They suggested seven factors that national authority should consider when determining decommissioning strategy: meeting policy requirements, availability of resources, costs, spent fuel and radioactive waste management, safety and security, regulatory aspects, multiple facilities, knowledge management, social and economic impacts, and stakeholder considerations.

IAEA (2011) [7] also provides policies and strategies guideline for the decommissioning of nuclear and radiological facilities. A decommissioning policy is a set of established goals or requirements for the safe and effective decommissioning of nuclear facilities. The policy should enable a graded approach to be taken to decommissioning, reflecting the level of the hazard posed by the facility to be decommissioned and its complexity. It emphasizes the decommissioning of nuclear power plant should provide protection of people and the environment, a long-term commitment to ensuring sites and waste, efficiency in the use of resources, open and transparent interactions with stakeholders, and participation in decision making to the public. All these requirements should be considered when budgeting a decommissioning project cost. Examples of the main elements to be considered in establishing a national policy for decommissioning are allocation of responsibilities, provision of resources, decommissioning approaches, safety and security objectives, radioactive waste management, hazardous waste minimization, end points for decommissioning, and public information and participation.

ENRESA (2017) [8] case also shows that the increase in the project management period due to delays, a strengthened regulatory requirement, and a change in site restoration requirements can significantly affect the actual decommissioning costs of NPP.

Following the previous research, we identified several candidates for explanatory variables, which can represent the cost drivers. The selected candidates are plant capacity, commercial operation period, ratio of operation to total hours, lifetime quantity of electricity generated during operation period, duration of decommissioning work, real GDP per capita, regulatory site release criteria, reactor types, decommissioning strategies (deferred, immediate, entombment). These variables are available by document research and rationally considered as proxies to the individual causes in part or in collective manner, even though some of them may not be original cause of decommissioning cost.

As of September 2020, 187 nuclear power reactors are permanently shut down. We investigated 123 documents [11-133] to collect historical decommissioning costs along with candidate explanatory variables data, which result is summarized in the [Appendix 1]. Most of them are decommissioned whereas some of them are in progress or planning. All the monetary values are converted into USD, as of FY 2019. The examples of collected items are the actual degree of contamination, in line with the specific release criteria and clean-up levels applied for the plants, technological approaches adopted for dismantling and demolition. For waste management, there is considerable variation to the extent to which the estimates provided incorporate these costs. It is reasonable to expect waste management costs as an increasing function of waste volumes, which may be proportional to capacity, operating period, or efficiency.

3. Research data and model

We build regression models based on a hypothesis that decommissioning cost is determined by plant specification factors, operation characteristics, and decommissioning work. The plant type is treated as a discrete variable to check systematic difference between plant specifications. Following the Han et al. (2020), we try building a synthetic variable of contamination, which reflects the operation characteristics. The plant capacity, year of operation, and efficiency factors are selected to represent the degree or waste of contamination. We include the duration of decommissioning work, level of wage, decommissioning strategy, and minimum environmental requirement as factors for decommissioning work. On top of the former research, we will develop enhanced 2SLS regression analysis to find out more reliable determinants and forecasting formula. Additionally, we will try to suggest model for BWR, which was not able to be explained in previous research.

First, we perform pooled OLS (Ordinary Least Squares) regressions to find out statistically effective determinants on decommissioning cost. Especially, the contamination variable is tested. Second, we improve the first result by substituting and testing a possibility of instrumenting the contamination with the three operation factors: the plant capacity, year of operation, and efficiency. In case it is statistically reliable, we develop a 2SLS (Two Stage Least Squares) models [10]. Finally, we will perform Monte-Carlo Simulation to illustrate the fitness of estimation formula that is derived from the 2SLS parameters.

3.1 Data and statistics

The definitions of selected variables, as discussed in the

Table 1. Definition and explanation of variables

Variable	Definition	Units	Reference
dcost	decommissioning cost of nuclear power reactor	million USD	[19-133]
capa	capacity of nuclear power reactor	MW	[11]
opyear	operation period of nuclear power reactor from the beginning of commercial operation to shutdown	years	[11]
eff	ratio of operation hours against total hours	percent	[11]
genq	total quantity of electricity generated during operation period	TWh	[11]
workyear	decommissioning duration of nuclear power reactor	years	[19-133]
wage	Average GDP per capita at beginning of decommissioning work, modified into 2019 price with GDP deflator	USD	[12-14]
criteria	nuclear power plant site release criteria	mSv per yr	[15-18, 51]
type	nuclear power reactor type: others(*) = 0, PWR = 1, BWR = 2	discrete	[19-133]
str	decommissioning strategy of nuclear power reactor: deferred = 0, immediate = 1	discrete	[19-133]

(*) PHWR, GCR, LWGR, FBR, and so on

Table 2. Basic statistics

Variable	Observation	Mean	Std. Dev.	Min.	Max.
dcost	100	797.49	488.79	74.37	2,527.00
capa	100	1,536.24	1,128.99	58.00	4,800.00
opyear	100	29.27	11.04	1.33	48.79
eff	100	74.60	14.18	26.80	94.50
genq	100	82.65	78.31	0.32	315.58
workyear	100	40.07	27.74	5.41	88.00
wage	100	45,099.95	13,860.11	1,308.32	80,212.29
criteria	100	0.07	0.10	0.01	0.25
type*	100	0.79	0.77	0.00	2.00
str	100	0.45	0.50	0.00	1.00

* Number of reactor type: others = 42, PWR = 37, BWR = 21
** All the monetary values are transferred into USD as of FY 2019

above ‘2. Literature Review’, are summarized in the above table.

We collected 187 cases of decommissioning data [Appendix]. And 87 cases are excluded through a data cleaning process (deleting cases with omitted information, irrational value, experimental plants, etc.). As a result, 100 cases are applied to the empirical test. The basic statistics of the data set is summarized in the above table.

3.2 OLS (Ordinary Least Squares) model

Radionuclide waste is generated by neutron irradiation and contamination caused by leaked radionuclides during reactor operation. According to IAEA (1998) [9], for all reactor types, the radionuclide composition of activated and contaminated materials may vary with a wide range. A detailed assessment is required including operational information, history, and on-site sampling of nuclear power plants for all the individual cases, which is not feasible. And thus, a proxy variable is required for a modelling purpose. The variation is influenced by numerous factors, among which important ones are the integrated neutron flux, the duration of the operation and the time elapsed after reactor shutdown. In addition, for similar nuclear power plants, the higher the reactor power output, the higher the neutron fluxes and hence the higher the amount of activation products. IAEA (1998) also guides that, with respect to decommissioning a nuclear power plant, an assessment of radionuclide inventory characterization should be carried out to predict the costs of decommissioning, as well as relevant action plan. Considering the above discussions and relevant factors from Joo et al. (2020) [5], a contamination variable is constructed as follows:

$$contam_i = capa_i \times opyear_i \times eff_i \quad (1)$$

where, $contam_i$ = degree of contamination in case i

The OLS models are designed and tested based on the assumption that decommissioning cost may depend on the degree of radioactive contamination, factors related with decommissioning activity such as wage and duration, plant specification such as reactor types. The first set of decommissioning cost estimation models, including the '$contam_i$' variable, are as follows:

$$\text{ln\_dcost}_i = \alpha_0 + \alpha_1 \text{ln\_}contam_i + \alpha_2 \text{ln\_}workyear_i + \alpha_3 \text{ln\_}wage_i + \alpha_4 \text{ln\_}criteria_i + D_1 type_i + D_2 str_i + \varepsilon_i \quad (2)$$

where, ln_'var_i' = natural log of '$variable_i$', α_m = coefficients for estimation, D_n = coefficients for discrete variable, ε_i = error term of i

We use p-value in order to check the confidence interval. When a probability sample of n size is $\{x_1, x_2, \cdots, x_n\}$ from a population with a density function $f(x: \theta)$ with parameter θ, lower confidence limit $\theta_L = (\widehat{\emptyset_L})$ and upper confidence limit $\theta_H = (\widehat{\emptyset_H})$ for a given significance value of $0 < \alpha < 1$, satisfy $P(\widehat{\emptyset_L} < \theta < \widehat{\emptyset_H}) = 1-\alpha$ and when $\theta_L < \theta_H$, the intervals $[\theta_L, \theta_H]$ are called as $(1-\alpha)\times 100\%$ confidence level for parameter θ. And thus, it can be expressed as $P = \left(-Z_{\alpha/2} < \frac{\bar{X}-\mu}{\frac{\sigma}{\sqrt{n}}} < Z_{\alpha/2}\right) = 1-\alpha$. We use the STATA commercial tool for the robust OLS estimation.

3.3 2SLS (Two Stage Least Squares) model

The estimated coefficients in equation 2 may have critical problem if the synthetic variable of contam does not reliably mimic the degree of contamination for individual cases. We can reasonably doubt this possibility because the equation 1 is made simply by multiplying capa, opyear, and eff, instead of observed data or mathematical calculation. In short, we cannot verify whether the equation 1 is true or not. So, we apply 2SLS methodology to improve this issue, and suggest another explanatory variable that can be well instrumented by the three operational factors (capa, opyear, eff).

The 2SLS model can be expressed as combined equations of 3 and 4, which are the first and second steps respectively [10].

$$y_{i,2} = \pi_0 + \textstyle\sum_{j=1}^{m} \pi_k z_{i,j} + u_i \quad (3)$$

where, the $z_{i,j}$ are exogenous instrument variables, and the $y_{i,2}$ is endogenous explanatory variable.

$$y_{i,1} = \beta_0 + \beta_1 E(y_{i,2}) + \textstyle\sum_{k=2}^{n} \beta_k x_{i,k-1} + \text{v}_\text{i} \quad (4)$$

The equation 3 should be estimated through the first regression analysis and the $y_{i,2}$ be predicted. Again, the predicted $E(y_{i,2})$ is used as an explanatory variable in the equation 4. Basically, the 2SLS has been developed to cope with the endogeneity issue, which can be mathematically expressed as $cov(y_{i,2},v_i) \neq 0$ in the equation 4. The instrument variables 'zk' should be correlated with the endogenous explanatory variable '$y_{i,2}$' but should not be correlated with error term 'v_i'.

In our empirical analysis, we substitute the 'contam' variable with 'genq', which is the quantity of lifetime electricity generation of a system because it can be well instrumented by the three operational variables (capa, opyear, eff), which were used to explain the degree of contamination in equation 1. We can rationally establish the formula (5) instead of simply using (1) because variables in both the left and right sides can be observed.

$$\ln\_genq_i = \pi_0 + \pi_1 \ln\_capa_i + \pi_2 \ln\_opyear_i + \pi_3 \ln\_eff_i + u_i \quad (5)$$

Based on the equation 5, we test whether the estimated coefficients (π_n) are statistically reliable. And, if the result is acceptable, we use the genq as a proxy variable for the degree of contamination. Actually, this procedure coincides with the first step of 2SLS, which is discussed with the equation 3. Under this procedure, the capa, opyear, and eff are exogenous instrument variables ('$z_{i,j}$' in equation 3) that explain genq ('$y_{i,2}$' in equation 3).

In the second step, we regress dcost on E(genq) along with other explanatory variables such as workyear, wage, criteria, and type.

$$\ln\_dcost_i = \beta_0 + \beta_1 \ln\_E(genq)_i + \beta_2 \ln\_workyear_i + \beta_3 \ln\_wage_i + v_i \quad (6)$$

where, ln_'var_i' = natural log of '$variable_i$', β_k = coefficients for estimation, v_i=error term of i

We will use the STATA commercial tool for the 2SLS regression analysis and thus the estimated result will be fine-tuned statistically.

3.4 Probabilistic cost estimation

We will forecast decommissioning cost together with 95% of confidence intervals ($\hat{y}_i \pm t_{\alpha/2} \times SD(\hat{y})$), using the STATA commercial tool. The forecasted results are compared against the actual cost to show the fitness of the models.

And then, we will perform a Monte-Carlo simulation based on the derived formula along with the observed distributions of variables. We will use the Palisade Risk Analysis commercial tool.

4. Empirical test result

4.1 Result of OLS (Ordinary Least Squares)

We estimated the parameters of models from (1) to (6) based on the equation 2. The first group of models (1)–(3) are pooled regressions including all types of reactors. We also did regression analysis based on separate groups of reactors for the robustness check purpose. The result is summarized as the below table.

We proxied the quantity of radioactive waste with the contam variable, as identified in the equation 1. From the models (1) through (3), the contam variable seems statistically reliable. A comprehensive review from the models (1) through (3) suggest that the amount of radioactive waste or the radionuclide inventory may account for the decommissioning cost.

Both the workyear and wage show 99% of confidence level in all the models from (1) to (3), and at the same time, they provide stable parameter estimates. We may think the decommissioning duration and the level of labor cost per capita also affect to the decommissioning costs.

However, it is surprising to find out that the parameters

Table 3. Decommissioning Cost Estimation (Robust OLS models)

Vasriables	Pooled Regression			type 0	type 1	type 2
	(1)	(2)	(3)	(4)	(5)	(6)
	ln_dcost	ln_dcost	ln_dcost	ln_dcost	ln_dcost	ln_dcost
ln_contam	0.228***	0.253***	0.258***	0.0130	0.161	0.372***
	(0.0472)	(0.0449)	(0.0444)	(0.0753)	(0.104)	(0.126)
ln_workyear	0.263***	0.279**	0.207***	0.479***	0.478***	−0.0757
	(0.0841)	(0.125)	(0.0716)	(0.130)	(0.126)	(0.208)
ln_wage	0.342***	0.280***	0.286***	−1.078*	0.391***	0.650
	(0.115)	(0.101)	(0.101)	(0.573)	(0.0563)	(0.487)
ln_criteria	−0.0185					
	(0.0483)					
1.type	0.259					
	(0.161)					
2.type	−0.0101					
	(0.160)					
1.str		0.131				
		(0.188)				
Constant	−1.528	−1.191	−1.016	15.88**	−1.401	−5.767
	(1.466)	(1.291)	(1.263)	(6.536)	(1.389)	(4.265)
Observations	100	100	100	42	37	21
R-squared	0.369	0.346	0.343	0.469	0.509	0.476

*Robust Standard Errors in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

of the criteria and str are different from expectation. As is shown from models (1) to (3), the difference in minimum environmental requirement criteria, and decommissioning strategies would not significantly affect the overall decommissioning cost. We may conclude that decommissioning strategy and minimum environmental requirement criteria do not significantly change the total cost. As the strategy is closely related with workyear variable, it could have caused a multicollinearity issue.

Again, we separated groups based on the three reactor types and performed same robust regression analysis as in models from (4) to (6). The results show that the estimated coefficients not only for contam but also for workyear and wage are significantly different among reactor types. We conclude that the groups with different type of reactors are heterogeneous, and thus the pooled OLS regression cannot be applied. It is also found that the contam variable is valid only in the type 2 group, and thus we conclude that the contam variable cannot be accepted properly as proxy variable for the degree of radioactive waste.

4.2 Result of 2SLS (Two Stage Least Squares)

Using the same dataset, we performed 2SLS analysis as suggested by the equations from 3 through 6 with each group of reactor types: the type 0 is others, type 1 is PWR,

Table 4. Decommissioning Cost Estimation (2SLS model)

Vasriables	(7) type 0		(8) type 1		(9) type 2	
	First Stage	Second Stage	First Stage	Second Stage	First Stage	Second Stage
	ln_genq	ln_dcost	ln_genq	ln_dcost	ln_genq	ln_dcost
ln_genq		0.117**		0.284***		0.353***
		(0.0551)		(0.108)		(0.107)
ln_capa	1.072***		1.214***		1.064***	
	(0.0402)		(0.128)		(0.0166)	
ln_opyear	0.696***				1.084***	
	(0.0667)				(0.0481)	
ln_eff	1.032***		1.567***		0.725***	
	(0.155)		(0.438)		(0.138)	
ln_workyear	0.0664	0.341***	0.0206	0.462***		
	(0.0568)	(0.0899)	(0.121)	(0.130)		
ln_wage			0.162*	0.334***	−0.00973	0.676*
			(0.0906)	(0.102)	(0.0696)	(0.414)
Constant	−10.79***	4.735***	−13.15***	0.403	−10.04***	−2.276
	(0.534)	(0.361)	(2.297)	(1.089)	(0.746)	(4.158)
Observations	42	42	37	37	21	21
R-squared	0.974	0.352	0.789	0.493	0.996	0.462

*Genq is instrumented by the capa, opyear, eff, and workyear, where the capa, opyear, and eff are explanatory variables for genq but the workyear is exogeneous variable in model (7).
**Standard Errors in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

and type 2 is BWR. The result is summarized in the below table: From the Table 4, the first stage estimators show the genq can be rationally instrumented by the three explanatory variables: capa, opyear, and eff. We included three of them in model (7) and (9), and two of them in model (8), considering p-values. The range of R-squared values are from 78.9% to 99.6%, which result verifies there is no concern for a ‘weak instrument problem’ for the 2SLS methodology. And the estimated coefficients of capa, opyear, and eff are statistically significant under 99% confidence level.

After the 2SLS regressions, we performed the Sargan and Basmann tests to check overidentification issue. We also did Durbin and Wu-Hausman tests to check endogeneity. In overall, the model (8) shows the best result for using 2SLS. The result in model (7) is not satisfactory but close to 90% of criteria in confidence levels. The model (9) does not have overidentification issue. But there is no evidence of endogeneity so simple OLS estimator can be used instead of 2SLS for the model (9). However, we select the 2SLS because it improved parameters and R-squared values. In summary, we have no reason to reject 2SLS methodology for the models from (7) through (9).

From the three test results of Table 4, we found that 2SLS regression can generate better estimators than simple OLS, and the genq can be properly instrumented by the three operational variables, which represent the compara-

Table 5. Overidentification and endogeneity tests

Issues	Tests	Model (7)	Model (8)	Model (9)
Overidentification	Sargan chi2	4.31 (p = 0.11)	10.23 (p = 0.00)	5.04 (p = 0.08)
	Basmann chi2	4.23 (p = 0.12)	12.23 (p = 0.00)	5.06 (p = 0.07)
Endogeneity	Durbin chi2	2.40 (p = 0.12)	5.06 (p = 0.02)	0.16 (p = 0.68)
	Wu-Hausman	2.30 (p = 0.13)	5.08 (p = 0.03)	0.16 (p = 0.69)

tive amount of radioactive waste.

The estimated parameters can be translated as elasticity because all variables are in the form of natural logarithm. Based on the second stage estimators in models (7) through (9), it is found that the instrumented E(genq) variable is statistically reliable. The results can be translated that if genq, or level of radioactive waste, increase one percent, the decommissioning cost increase 11.7% in type 0, 28.4% in type 1, and 35.3% in type 2 reactors.

The workyear, duration of decommissioning, makes critical impact on type 0, and type 1 reactors. It is found that, if the duration increases one percent, the decommissioning cost increase 34.1% and 46.2%, respectively. The wage, which is a comparative level of labour cost, affects 33.4% and 67.6% to type 1 and type 2 reactors by one percent change.

Similar to the OLS analysis result, it is proved that decommissioning strategy and environmental requirements do not significantly change the decommissioning cost. It seems that the duration factor reflected most of the strategy effect.

In summary, we conclude that level of radioactive waste along with the decommissioning duration and the level of labor cost per capita significantly determine the decommissioning cost. And the level of radioactive waste can be explained by the operation factors such as period of operation, capacity of plant, and efficiency.

The decommissioning cost of PWR type is significantly determined by plant capacity, efficiency, duration of decommissioning work, and level of wage. The capacity factor may impact thorough two routes: increasing the dimension of structure as well as radioactive waste. Both the capacity and efficiency factors explain the degree of radioactive waste by instrumenting the total electricity generation. The duration of work and level of wage explain themselves. Additionally, we infer the cost impact from the different decommissioning strategies is already reflected by the duration of work because they are highly correlated. The site release criteria have smaller value in stricter countries and thus negatively correlated to cost, which direction is reasonably shown in the model (1) of Table 3. However, this variable is not selected as one of major determinants due to lack of confidence.

The decommissioning cost of BWR type is mainly determined by plant capacity, operation period, efficiency, and level of wage. The BWR type additionally includes the operation period, which explains the degree of radioactive waste, however it does not include the duration of decommissioning work as a major cost determinant. The operation period not only the capacity and efficiency factors explain the degree of radioactive waste by instrumenting the total electricity generation in this group.

Even though the main purpose of current study is to investigate determinants of decommissioning cost, we formulate the cost estimation models for simulation purpose. The equation 7 is derived from the model (8) of Table 4 and

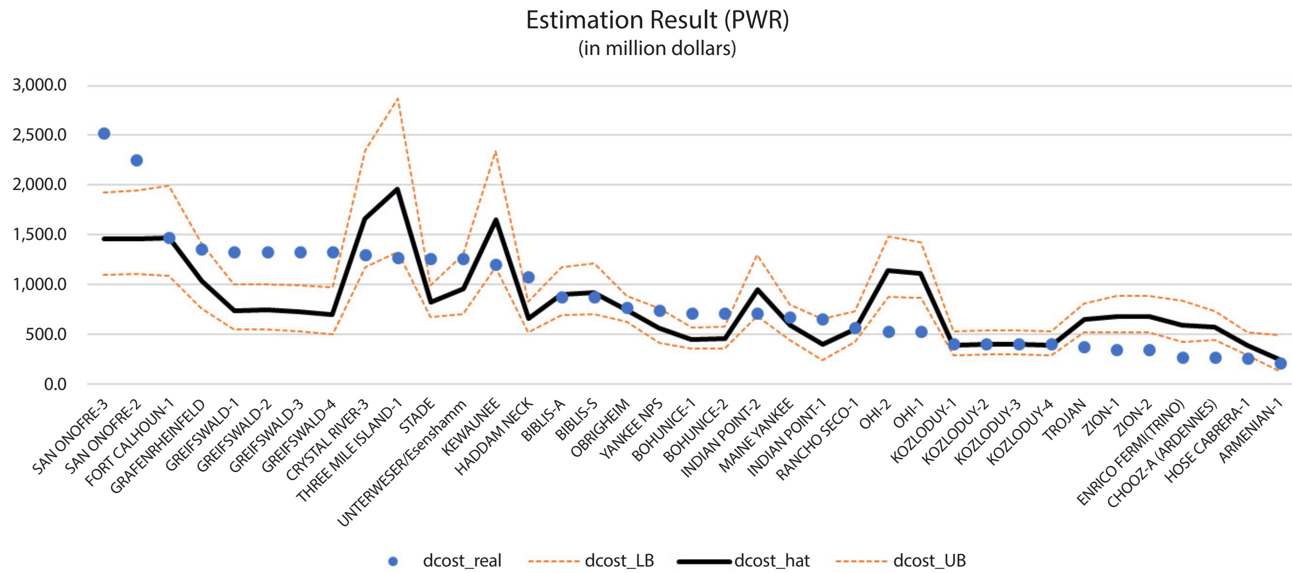

Fig. 1. Cost estimation result for type 1 (PWR).

*dcost_real = historical decommissioning cost expressed in real (year of 2019) value; dcost_LB = lower bound of estimated cost with 95% confidence level; dcost_hat = point estimation of decommissioning cost based on the equation 7; dcost_UB = higher bound of estimated cost with 95% confidence level.

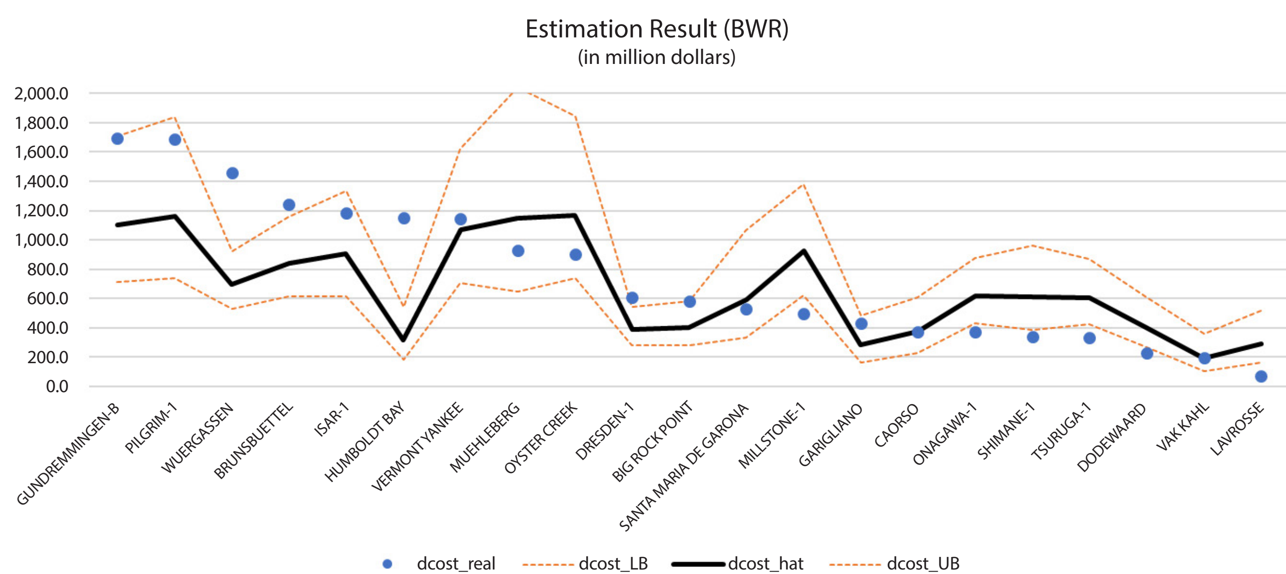

Fig. 2. Cost estimation result for type 2 (BWR).

*dcost_real = historical decommissioning cost expressed in real (year of 2019) value; dcost_LB = lower bound of estimated cost with 95% confidence level; dcost_hat = point estimation of decommissioning cost based on the equation 7; dcost_UB = higher bound of estimated cost with 95% confidence level.

Table 6. Input data for KORI-1 [134]

Reactor	type	dcost(*) [M USD]	genq [TWh]	capa [MW]	workyear [year]	opyear [year]	eff [%]
KORI-1	1 (PWR)	714.4	148.6	1,729.0	15.5	39.1	79.5

(*) expressed as real value (year of 2019) basis.

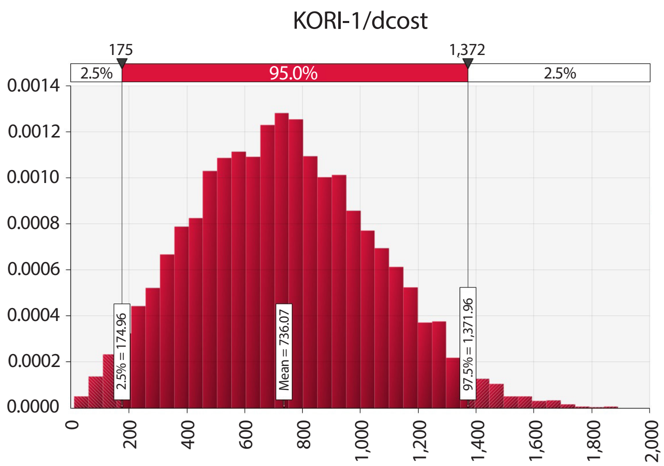

Fig. 3. Monte-Carlo simulation result.

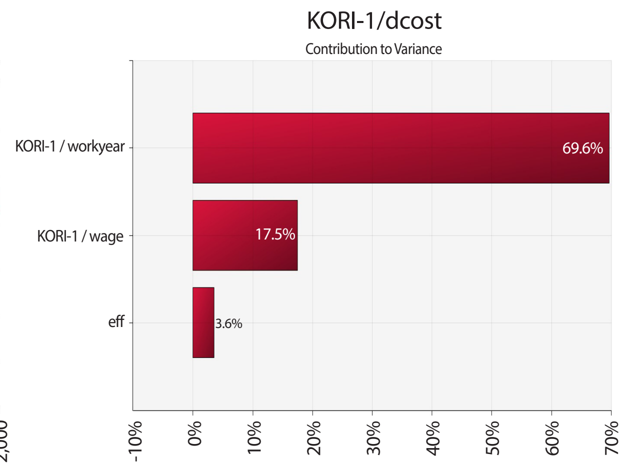

Fig. 4. Degree of contribution to variance.

corresponds to type 1 reactors (PWR).

$$dcost_i = capa_i^{0.344} \times eff_i^{0.445} \times workyear_i^{0.467} \times wage_i^{0.379} \times e^{-3.328} \quad (7)$$

We also present the equation 8, which is derived from the model (9) of Table 4 and accounts for type 2 (BWR) reactors.

$$dcost_j = capa_j^{0.375} \times eff_j^{0.256} \times opyear_j^{0.382} \times wage_j^{0.672} \times e^{-5.820} \quad (8)$$

5. Simulation

We performed static cost estimation using the STATA commercial tool based on the models (8) and (9) of Table 4. After the static cost estimation, we also drew 95% of confidence intervals ($\hat{y}_i \pm t_{\alpha/2} \times SD(\hat{y})$). The input data for individual cases are from the [Appendix]. The monetary values are million USD basis as of FY 2019. The cost estimation result and their actual cost are illustrated in Fig. 1 and 2.

The Fig. 1 shows that the estimation results tend to have deviation from the actual value among the cases with high and low levels of decommissioning costs. We conclude that the model (8) fits well for PWR type NPPs with decommissioning costs from 1,265 mil to 400 mil USD. The Fig. 2 shows a little bit different range of fitness of the model (9) for BWR NPPs from 1,963 mil to 376 mil USD of decommissioning costs.

We performed the same cost estimation process for the KORI-1, which case was reserved (excluded from the regression modelling). The input data of KORI-1 is as follows: The estimated static decommissioning cost of KORI-1 is 691.7 mil USD (in 2019 FY value), which is about 3.1% lower than the authority's official estimation of 714.4 mil

USD (in 2019 FY value). The 95% confidence interval is calculated as [554 mil, 862 mil] by the STATA statistics tool.

We again performed a Monte Carlo Simulation for the KORI-1 as illustrated in Fig. 3. The input data of Table 6 along with the standard deviations from Table 2 are applied to the equation 7. We ran 10,000 times of simulation with the PALISADE tool.

The most likely estimation value is 736.07 mil USD, which is 3.03% higher than the authority's estimation. The 95% confidence interval is calculated as [175 mil, 1,372 mil]. The Fig. 4 illustrates the input variables that have critical impact and their degree of contributions to output variance. The capa variable could have been reported as one of the highly determining factors, in case we forecast decommissioning cost for unidentified project, but we did not include it as one of simulation variables because there is low possibility of deviation once the KORI-1 plant is constructed.

6. Conclusion

The empirical tests showed that the level of radioactive waste along with the decommissioning duration and the level of labor cost per capita significantly determine the decommissioning cost. And the degree of radioactive waste can be explained by the operation factors such as period of operation, capacity of plant, and efficiency.

We found that the plant groups with different type of reactors are heterogeneous, and thus the pooled OLS regression cannot be applied. And the contam variable has a shortfall of not testable. For the purpose of improving this issue, we applied 2SLS methodology and suggested genq variable, which could be instrumented by the three operational factors (capa, opyear, eff). From the test results of Table 4, we found that 2SLS regression analysis can generate better estimators than simple OLS. And the genq can be properly instrumented by the three operational variables, which represent the comparative amount of radioactive waste.

The results can be translated that, if the level of radioactive waste (measured by proxy variables) increases one percent, the decommissioning cost increases 28.4% in the PWR type NPPs. The cost increases 46.2% and 33.4% due to one percent increase in work duration and level of labour cost, respectively. The test results also present that the decommissioning cost increases 35.3% in the BWR type NPPs, if the level of radioactive waste (measured by proxy variables) increases one percent. The cost also increases 67.6% due to one percent increase in labour cost level.

We illustrated static cost estimation as well as confidence intervals in Fig. 1 and 2, using the STATA statistics tool. We did the same analysis on the KORI-1. The most likely value is estimated at 691.7 mil USD and the 95% interval is calculated at [554 mil, 862 mil], where the authority's official estimation is 714.4 mil USD. The Monte-Carlo simulation provided 736.07 mil USD of the most likely value and [175 mil, 1,372 mil] of the 95% confidence level.

As the second stage R-squared values of models (8) and (9) in Table 4 indicate, we clearly admit that the cost estimation models (equation 7 and 8 can explain only 49% for PWR and 46% for BWR type NPPs. The forecasting ability will be enhanced either by adding determining factors or improving models through further studies.

Acknowledgment

This research was supported by grants from the New & Renewable Energy Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) funded by the Korean Ministry of Trade, Industry and Energy (MOTIE) (Project No. 20194010000090. This work was supported by the 2020 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.

Appendix 1. Prmanent shutdown nuclear power reactors [19-133]

Country	Reactor	Type	Capa. (MWth)	Op. factor (%)	Total generation (TWh)	Decom. work period	Cost (M USD)
ARMENIA	ARMENIAN-1	PWR	1,375	67.8	25.3	50	212.0
BELGIUM	BR-3	PWR	41	51.5	0.8	21	10.7
BULGARIA	KOZLODUY-1	PWR	1,375	73.0	61.1	18	401.1
	KOZLODUY-2	PWR	1,375	79.2	62.8	18	401.1
	KOZLODUY-3	PWR	1,375	81.4	62.8	18	401.1
	KOZLODUY-4	PWR	1,375	82.6	61.0	18	401.1
CANADA	DOUGLAS POINT	PHWR	704	67.1	15.6	NA	-
	GENTILLY-1	HWL WR	792	7.5	0.8	3	-
	GENTILLY-2	PHWR	2,156	81.2	124.2	54	1,098.7
	PICKERING-2	PHWR	1,744	62.5	71.4	59	520.5
	PICKERING-3	PHWR	1,744	70.8	80.0	59	520.5
	ROLPHTON NPD	PHWR	92	72.4	3.2	NA	-
FRANCE	BUGEY-1	GCR	1,954	70.1	55.3	18	509.3
	CHINON A-1	GCR	300	39.8	3.0	53	333.8
	CHINON A-2	GCR	800	75.0	24.9	44	333.8
	CHINON A-3	GCR	1,170	49.1	30.6	22	333.8
	CHOOZ-A	PWR	1,040	71.0	38.6	18	272.0
	EL-4	HWGCR	250	75.4	6.3	12	461.1
	FESSENHEIM-1	PWR	2,785	74.0	225.7	NA	-
	FESSENHEIM-2	PWR	2,785	71.9	216.9	NA	-
	G-2 (MARCOULE)	GCR	260	66.2	0.9	NA	-
	G-3 (MARCOULE)	GCR	260	78.8	10.5	NA	-
	PHENIX	FBR	345	41.2	24.4	14	1,074.6
	ST. LAURENT A-1	GCR	1,650	71.9	45.3	27	330.9
	ST. LAURENT A-2	GCR	1,475	64.4	46.9	22	330.9
	SUPER-PHENIX	FBR	3,000	14.4	3.4	18	1,165.7
GERMANY	AVR JUELICH	HTGR	46	65.9	1.5	33	922.6
	BIBLIS-A	PWR	3,517	68.7	232.8	16	878.0
	BIBLIS-B	PWR	3,733	74.5	247.4	16	878.0
	BRUNSBUETTEL	BWR	2,292	57.9	120.4	15	1,240.2
	GRAFENRHEINFELD	PWR	3,765	88.7	315.6	18	1,354.8
	GREIFSWALD-1	PWR	1,375	84.6	35.5	34	1,324.8
	GREIFSWALD-2	PWR	1,375	85.1	36.6	34	1,324.8
	GREIFSWALD-3	PWR	1,375	82.5	33.3	34	1,324.8
	GREIFSWALD-4	PWR	1,375	79.4	28.9	34	1,324.8
	GREIFSWALD-5	PWR	1,375	0.0	0.0	34	1,324.8

Country	Reactor	Type	Capa. (MWth)	Op. factor (%)	Total generation (TWh)	Decom. work period	Cost (M USD)
	GUNDREMMINGEN-A	BWR	801	81.2	13.8	47	2,782.3
	GUNDREMMINGEN-B	BWR	3,840	90.4	314.5	22	1,693.5
	HDR GROSSWELZHEIM	BWR	100	42.4	0.0	16	-
	ISAR-1	BWR	2,575	86.0	198.3	16	1,182.9
	KNK II	FBR	58	26.8	0.3	31	475.0
	KRUEMMEL	BWR	3,690	69.2	201.7	NA	-
	LINGEN	BWR	520	42.2	9.1	NA	-
	MUELHEIM-KAERLICH	PWR	3,760	76.0	10.3	21	1,036.6
	MZFR	PHWR	200	73.3	4.8	35	449.0
	NECKARWESTHEIM-1	PWR	2,497	84.7	186.8	16	-
	NIEDERAICHBACH	HWGCR	321	9.0	0.0	20	173.6
	OBRIGHEIM	PWR	1,050	83.7	86.8	17	770.1
	PHILIPPSBURG-1	BWR	2,575	80.3	187.6	21	-
	PHILIPPSBURG-2	PWR	3,950	88.2	347.1	20	-
	RHEINSBERG	PWR	265	NA	NA	31	1,153.2
	STADE	PWR	1,900	85.3	145.9	16	1,264.7
	THTR-300	HTGR	760	56.0	2.8	33	837.2
	UNTERWESER	PWR	3,900	83.7	289.8	15	1,264.7
	VAK KAHL	BWR	60	67.8	2.1	22	194.6
	WUERGASSEN	BWR	1,912	71.9	69.7	17	1,461.1
ITALY	CAORSO	BWR	2,651	43.5	27.7	32	376.0
	ENRICO FERMI(TRINO)	PWR	870	50.0	24.3	32	273.2
	GARIGLIANO	BWR	506	44.8	12.3	27	432.4
	LATINA	GCR	660	71.7	25.5	28	316.1
JAPAN	FUGEN ATR	HWL WR	557	63.7	8.5	31	623.2
	FUKUSHIMA-DAIICHI-1	BWR	1,380	56.1	82.4	39	-
	FUKUSHIMA-DAIICHI-2	BWR	2,381	64.3	148.2	39	-
	FUKUSHIMA-DAIICHI-3	BWR	2,381	67.6	155.9	39	-
	FUKUSHIMA-DAIICHI-4	BWR	2,381	71.9	154.3	39	-
	FUKUSHIMA-DAIICHI-5	BWR	2,381	67.5	156.4	NA	-
	FUKUSHIMA-DAIICHI-6	BWR	3,293	65.3	206.7	NA	-
	FUKUSHIMA-DAINI-1	BWR	3,293	59.4	205.7	NA	-
	FUKUSHIMA-DAINI-2	BWR	3,293	57.2	190.6	NA	-
	FUKUSHIMA-DAINI-3	BWR	3,293	51.2	163.1	NA	-
	FUKUSHIMA-DAINI-4	BWR	3,293	53.8	161.4	NA	-
	GENKAI-1	PWR	1,650	69.0	127.7	27	332.8
	GENKAI-2	PWR	1,650	64.2	118.2	35	325.0

Country	Reactor	Type	Capa. (MWth)	Op. factor (%)	Total generation (TWh)	Decom. work period	Cost (M USD)
	HAMAOKA-1	BWR	1,593	50.1	73.6	27	-
	HAMAOKA-2	BWR	2,436	60.8	129.6	27	-
	IKATA-1	PWR	1,650	69.9	125.7	40	364.3
	IKATA-2	PWR	1,650	68.4	115.9	38	-
	JPDR	BWR	90	0.1	0.0	15	181.4
	MIHAMA-1	PWR	1,031	50.2	60.1	29	295.3
	MIHAMA-2	PWR	1,456	58.6	101.6	29	326.4
	MONJU	FBR	714	0.0	0.0	30	1,342.1
	OHI-1	PWR	3,423	56.0	213.3	29	530.2
	OHI-2	PWR	3,423	61.5	231.7	29	532.0
	ONAGAWA-1	BWR	1,593	52.6	81.8	34	375.3
	SHIMANE-1	BWR	1,380	64.7	101.9	29	341.9
	TOKAI-1	GCR	587	78.6	28.2	29	828.0
	TSURUGA-1	BWR	1,070	62.4	80.1	23	331.9
KAZAKHSTAN	AKTAU	FBR	1,000	51.6	1.9	NA	-
KOREA, REP. OF	KORI-1	PWR	1,729	79.5	148.6	16	714.4
	WOLSONG-1	PHWR	2,061	68.7	140.3	NA	-
LITHUANIA	IGNALINA-1	LWGR	4,800	68.5	86.4	26	1,962.1
	IGNALINA-2	LWGR	4,800	76.0	155.2	26	1,962.1
NETHERLAND	DODEWAARD	BWR	183	86.0	10.9	NA	227.8
RUSSIA	APS-1 OBNINSK	LWGR	30	NA	NA	NA	-
	BELOYARSK-1	LWGR	286	NA	NA	NA	-
	BELOYARSK-2	LWGR	530	72.1	22.0	NA	-
	BILIBINO-1	LWGR	62	75.0	2.1	NA	-
	LENINGRAD-1	LWGR	3,200	73.1	244.1	33	227.3
	NOVOVORONEZH-1	PWR	760	NA	NA	NA	-
	NOVOVORONEZH-2	PWR	1,320	71.1	49.9	NA	-
	NOVOVORONEZH-3	PWR	1,375	80.3	109.3	NA	-
SLOVAKIA	BOHUNICE A1	HWGCR	560	52.4	0.9	54	505.6
	BOHUNICE-1	PWR	1,375	79.2	71.6	13	717.3
	BOHUNICE-2	PWR	1,375	80.8	77.0	13	717.3
SPAIN	JOSE CABRERA-1	PWR	510	78.9	34.6	11	258.2
	SANTA MARIA DE GA-RONA	BWR	1,381	81.6	127.0	11	528.4
	VANDELLOS-1	GCR	1,670	86.0	53.6	5	133.8
SWEDEN	AGESTA	PHWR	80	43.4	0.4	NA	10.7
	BARSEBACK-1	BWR	1,800	81.4	93.8	15	273.6

Country	Reactor	Type	Capa. (MWth)	Op. factor (%)	Total generation (TWh)	Decom. work period	Cost (M USD)
	BARSEBACK-2	BWR	1,800	81.8	108.0	15	213.0
	OSKARSHAMN-1	BWR	1,375	65.0	110.3	11	164.3
	OSKARSHAMN-2	BWR	1,800	75.8	154.0	12	199.8
	RINGHALS-2	PWR	2,652	73.7	216.1	8	209.1
SWITZERLAND	LUCENS	HWGCR	28	NA	NA	10	-
	MUEHLEBERG	BWR	1,097	90.4	122.5	15	931.0
UK	BERKELEY-1	GCR	620	82.4	21.0	87	806.2
	BERKELEY-2	GCR	620	82.9	21.6	87	806.2
	BRADWELL-1	GCR	481	83.9	27.2	86	801.9
	BRADWELL-2	GCR	481	83.9	27.2	86	801.9
	CALDER HALL-1	GCR	268	82.3	14.0	92	-
	CALDER HALL-2	GCR	268	82.7	14.0	92	-
	CALDER HALL-3	GCR	268	82.7	14.0	92	-
	CALDER HALL-4	GCR	268	82.7	14.0	92	-
	CHAPELCROSS-1	GCR	260	94.2	14.2	82	598.0
	CHAPELCROSS-2	GCR	260	94.2	14.2	82	598.0
	CHAPELCROSS-3	GCR	260	94.2	14.2	82	598.0
	CHAPELCROSS-4	GCR	260	94.2	14.2	82	598.0
	DOUNREAY DFR	FBR	60	34.5	0.5	17	-
	DOUNREAY PFR	FBR	600	38.2	7.1	17	-
	DUNGENESS A-1	GCR	840	86.5	59.2	85	863.0
	DUNGENESS A-2	GCR	840	86.9	60.7	85	863.0
	HINKLEY POINT A-1	GCR	900	89.0	46.5	86	494.1
	HINKLEY POINT A-2	GCR	900	89.0	46.5	86	494.1
	HUNTERSTON A-1	GCR	595	94.5	28.7	85	963.0
	HUNTERSTON A-2	GCR	595	94.5	28.7	85	963.0
	OLDBURY A-1	GCR	730	85.5	62.3	87	981.7
	OLDBURY A-2	GCR	660	88.9	65.6	87	981.7
	SIZEWELL A-1	GCR	1,010	84.3	56.8	83	848.6
	SIZEWELL A-2	GCR	1,010	80.9	53.3	83	848.6
	TRAWSFYNYDD-1	GCR	850	92.0	35.2	88	821.3
	TRAWSFYNYDD-2	GCR	850	92.0	35.2	88	821.3
	WINDSCALE AGR	GCR	120	56.8	3.3	29	-
	WINFRITH SGHWR	SGHWR	318	60.9	11.0	28	-
	WYLFA-1	GCR	1,650	82.3	126.5	86	946.4
	WYLFA-2	GCR	1,920	82.5	109.3	86	946.4
UKRAINE	CHERNOBYL-1	LWGR	3,200	75.3	97.3	NA	-
	CHERNOBYL-2	LWGR	3,200	81.1	76.0	NA	-
	CHERNOBYL-3	LWGR	3,200	67.3	98.0	NA	-

Country	Reactor	Type	Capa. (MWth)	Op. factor (%)	Total generation (TWh)	Decom. work period	Cost (M USD)
	CHERNOBYL-4	LWGR	3,200	NA	NA	NA	-
USA	BIG ROCK POINT	BWR	240	73.0	12.7	9	582.7
	BONUS	BWR	50	NA	NA	3	-
	CRYSTAL RIVER-3	PWR	2,568	66.9	167.6	61	1,303.8
	CVTR	PHWR	65	NA	NA	42	-
	DRESDEN-1	BWR	700	70.6	16.5	43	611.7
	ELK RIVER	BWR	58	NA	NA	2	25.3
	FERMI-1	FBR	200	NA	0.0	1	26.2
	FORT CALHOUN-1	PWR	1,500	77.3	130.7	51	1,472.9
	FORT ST. VRAIN	HTGR	842	31.1	5.4	7	295.7
	GE VALLECITOS	BWR	50	NA	NA	NA	11.5
	HADDAM NECK	PWR	1,825	76.0	105.7	11	1,074.4
	HALLAM	SGR	256	NA	NA	3	17.0
	HUMBOLDT BAY	BWR	220	84.0	4.8	38	1,153.1
	INDIAN POINT-1	PWR	615	51.9	13.5	12	657.5
	INDIAN POINT-2	PWR	3,216	77.5	282.9	12	717.0
	KEWAUNEE	PWR	1,772	85.1	150.1	60	1,199.9
	LACROSSE	BWR	165	63.2	3.9	23	74.4
	MAINE YANKEE	PWR	2,630	73.0	118.7	8	672.8
	MILLSTONE-1	BWR	2,011	69.2	101.4	56	498.5
	OYSTER CREEK	BWR	1,930	78.2	196.2	18	900.4
	PATHFINDER	BWR	220	NA	NA	1	17.5
	PEACH BOTTOM-1	HTGR	115	71.2	1.4	41	268.0
	PILGRIM-1	BWR	2,028	75.8	193.6	63	1,690.2
	PIQUA	OCMR	46	NA	NA	1	-
	RANCHO SECO-1	PWR	2,772	46.4	44.8	13	572.5
	SAN ONOFRE-1	PWR	1,347	55.1	51.1	39	259.6
	SAN ONOFRE-2	PWR	3,438	77.1	219.2	39	2,256.1
	SAN ONOFRE-3	PWR	3,438	78.4	215.7	39	2,527.0
	SAXTON	PWR	24	NA	NA	1	11.2
	SHIPPINGPORT	PWR	236	NA	NA	4	184.4
	SHOREHAM	BWR	2,436	NA	NA	3	288.4
	THREE MILE ISLAND-1	PWR	2,568	77.0	245.1	64	1,268.0
	THREE MILE ISLAND-2	PWR	2,772	74.6	2.0	NA	1,313.1
	TROJAN	PWR	3,411	57.9	84.4	12	378.8
	VERMONT YANKEE	BWR	1,912	86.3	163.4	39	1,142.8
	YANKEE NPS	PWR	600	77.4	33.9	15	739.1
	ZION-1	PWR	3,250	63.9	124.4	10	343.7
	ZION-2	PWR	3,250	65.9	124.5	10	343.7

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